CASSINI ORBITER OPERATIONS LESSONS LEARNED FOR THE HUYGENS PROBE MISSION

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ABSTRACT:

The Huygens probe descended into the atmosphere of Titan on 14 January 2005. The data the probe transmitted was collected by the Cassini orbiter, which was autonomously controlled by the Probe Relay Critical Sequence. This paper documents the development and testing of the probe relay critical sequence that controlled the Cassini orbiter's turn to Titan, reception and recording of the probe data, and turn back to Earth. The operational experience of preparing, loading and executing the sequence during Huygens Entry, Descent, and Landing is described, as are the operational lessons learned during this important inter-agency collaborative engineering effort. Issues related to the International Traffic in Arms Regulations (ITAR), Export Administration Regulations (EAR), the co-location of ESA and NASA teams, interface agreements, requirements tracking, sequence testing, and spacecraft state tracking are discussed.

1 INTRODUCTION

The Cassini spacecraft was launched from Cape Canaveral on 15 October 1997. Piggybacking aboard Cassini was the ESA Huygens Probe. The Cassini mission includes flyby encounters with many of Saturn's moons and icy satellites, during a four-year tour of the Saturnian system. Huygens mission was to provide in-situ measurements of Titan's atmosphere and possibly of the surface, if the probe survived landing. The retrieval of the Huygens probe data was a key element to the success of the joint Cassini-Huygens mission.

1.1 Mission Background

Cassini executed a successful Saturn Orbit Insertion maneuver on 1 July 2004. On 25 December 2004, Cassini released the Huygens Probe, with only its on-board timer powered on, and counting down for a twenty day journey to the surface of Titan.

At 4:45 Universal Time (UT) on 14 January 2005 the Huygens Probe timer expired and the probe powered on in preparation for atmospheric entry. Following entry, the Probe descended through Titan's atmosphere, slowed by a series of three parachutes. During descent, a suite of six instruments collected unprecedented in-situ science data. The Huygens Probe Relay portion of the mission lasted for three hours and thirty nine minutes, during which the data collected was relayed back to the Cassini Orbiter. Following data collection, the Orbiter turned back to Earth and relayed Huygens' science data to the ground and thence to the science teams.

1.2 Distributed Mission Operations Team

The Cassini-Huygens Mission Operations Team is comprised of engineers and scientists from the US and Europe. Program management, core spacecraft engineering, and operational capabilities for the Cassini orbiter are based at the Jet Propulsion Laboratory (JPL) in Pasadena, California. Participating with the JPL teams are twelve instrument teams that are integral for orbiter instrument operations, health and safety. While some instrument teams reside at JPL, others are located at various government and university facilities in both the United States and Europe.

Huygens Project Management was based at the European Space Technology Centre (ESTEC) in Noordwijk, the Netherlands. While there were staff from ESA co-located at JPL to provide support to Huygens, the main mission operations center operated from the European Space Operations Centre (ESOC) in Darmstadt, Germany. In addition to the staff at ESOC and JPL, there are also six Huygens principle investigation (PI) teams. These science teams are based at various academic facilities in Europe and the United States.

Distributed operations across the United States and Europe presented many challenges. Detailed technical discussions and team interactions had to account for time differences and the availability of personnel. Daily interactions relied on the use of teleconferences and email, while support for major reviews and meetings required advance planning. Major reviews were conducted periodically to facilitate attendance by representatives from both ESA and NASA and promote face-to-face discussion.

2 SUCCESSFUL COLLABORATIVE EFFORTS

2.1 Huygens Recovery Task Force

An end-to-end in-flight test of the Probe Relay Link was performed on 3-4 February 2000 to characterize the behavior of the Huygens receiver, with particular emphasis on determining the signal and data detection thresholds. This test confirmed the expected carrier and subcarrier level performance, but there was unexpected behavior at the data level. Although the receiver performed nominally at zero-Doppler, data loss occurred when simulated mission Doppler corresponding to a relative velocity of ~5.6 km/s was applied to carrier, sub-carrier and data. In addition, unexpected loss of data was also observed at high values of link power.

An Investigation Team was set up in March 2000 to study this anomaly; subsequently, the Huygens Recovery Task Force (HRTF) was established in the winter of that year. The team performed a series of analyses to better understand the in-flight test results and several tests were performed on the Huygens Engineering Model to further characterize the receiver performance. These tests confirmed the receiver behavior observed in-flight and that the Huygens receivers would not be able to track the level of Doppler shift present during the descent of the probe. The major consequence of this anomalous behavior if left uncorrected would have been a substantial loss of probe data during the mission.

A joint ESA/NASA group of experts, the HRTF, was convened in January 2001 to understand the anomaly and recommend possible recovery actions. These actions required changing the link geometry as a function of time so as to stay away from regions where the Huygens receiver bit synchronizer loses lock on the data stream, resulting in Huygens data loss. This was achieved by increasing the fly-by altitude to 60000 km, reducing the Orbiter Delay Time (ODT), and by pre-heating the probe's transmitters to optimize the transmit frequency among other things. This approach resulted in a mission that was expected to deliver essentially 100% of the possible science data. The HRTF work was successfully concluded in July 2001.

A complete description of the work of the HRTF can be found in Ref. 2.

2.2 Huygens Implementation Team

The HRTF identified three specific programmatic recommendations. First, the redesigned mission would need to provide the Huygens mission with opportunities of low Doppler shift in the probe-orbiter radio link. This redesign impacted the early part of the Cassini Saturn Tour trajectory. Second, the Cassini orbiter was required to command the Probe Support Avionics (PSA) to base frequency - called BITE Mode - rather than searching for a signal at the expected Doppler frequency. BITE Mode was a PSA Test mode that held the lockup frequency at a level equivalent to –1 m/s relative velocity. The third mission recommendation was to pre-heat the probe's transmitters before probe descent to optimize the transmit frequency.

Implementation of these three recommendations was helped by co-locating some Huygens personnel at JPL. A Huygens Implementation Team (HIT) was formed at JPL and ESTEC with members from both the Cassini and Huygens projects. The HIT was comprised mainly of Navigation, Probe Systems and Cassini Systems personnel while other disciplines were involved as needed. Quarterly progress meetings with JPL and ESA were held to insure that all remaining issues with regard to the new mission design were addressed.

2.3 Cassini Probe Sequence Designs

2.3.1 Probe Release

The Probe Release was executed by a Cassini Orbiter command sequence. As part of the release strategy the Huygens Probe was powered off during the release with the exception of its countdown timer, powered from internal batteries. There was a six day window within which the probe could be released to achieve descent at the Titan-C flyby opportunity. The release of the Huygens Probe was commanded by the Cassini Command and Data Subsystem (CDS), with NASA Standard Initiators (NSI) at three attachment points on the Huygens Probe Spin-Eject Device (SED). The Cassini Pyrotechnic Subsystem is completely redundant, so there are 6 NSIs, 2 on each of the three Huygens attachment points. The Probe Release sequence has three main functions: turn to the release attitude, release the Probe, and finally turn back to Earth.

The original requirement on spacecraft pointing accuracy during release was +/- 9 degrees. The requirement was decreased to +/- 2 degrees to minimize possible excursion in the Probe Angle of Attack during entry. There was also a concern that slow convergence of orbit determination solutions may lead to late confirmation that probe entry requirements were met. Both these issues drove the mission design to support two possible release sequence updates; each update allowed the HIT to either slip the Probe release epoch and/or just update the release attitude.

The development of the Probe Release sequence was supported with appropriate reviews. A meeting was scheduled to assess all the Probe mission requirements on April 13, 2000. The intent of this meeting was to review all the requirements for both the Probe Release sequence and the Probe Relay sequence. The Release sequence was identified as a non-critical sequence. A critical sequence on Cassini is defined one that must continue to execute autonomously in the presence of spacecraft faults. A non-critical sequence will halt in the presence of a spacecraft fault, and will require ground intervention.

The makeup of the elements within HIT worked well for Probe Release. The primary issues for release were navigation, pointing and mission event timelines. Both Cassini and Huygens personnel participated in meetings, reviews, and simulations. All these issues could be addressed with the co-located members of the HIT.

2.3.2 Probe Relay

The Huygens Probe had minimal on-board data storage capability. The Probe must immediately transmit its data to the orbiter during the Huygens Entry, Descent, and Landing (EDL) phase of the mission; the Cassini Orbiter provided the bulk data storage capability for Huygens.

The Probe Relay sequence was built as a critical sequence. This decision to generate a critical sequence was necessary because ground intervention was not possible; the sequence had to be completely autonomous. The Probe Relay critical sequence had three main functions: to turn and track a Titan surface target (the expected Huygens landing site), to record critical data during the Probe Link and to turn back to Earth when the probe mission was completed.
A Cassini telemetry mode, called the PROBE_RELAY mode, was specifically designed to support the Huygens Probe mission. This mode routed all data to the online Command and Data Subsystem (CDS). The Prime CDS has the capability to listen in on the data traffic from every device on the spacecraft bus, so both CDSs received Huygens Probe data, and both CDSs

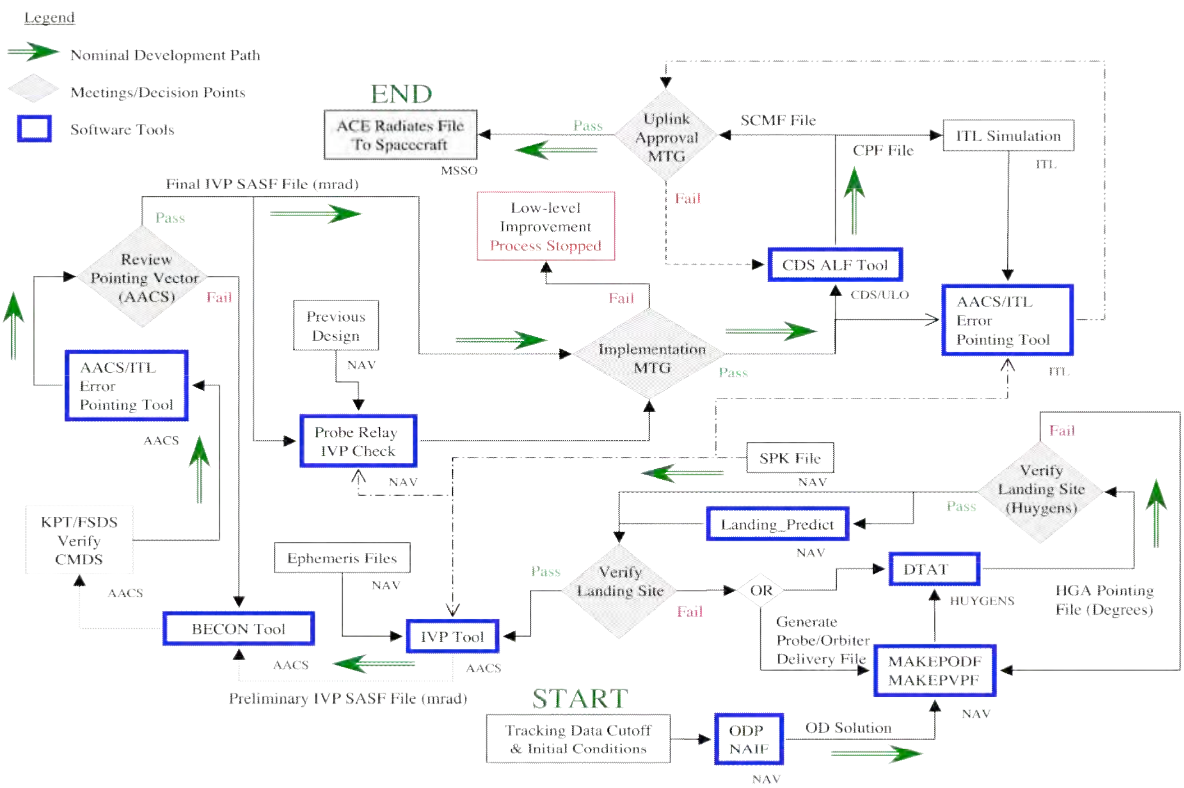

Figure 1. Probe Global Vector Update Process

duplicated the critical data. Critical data consisted of critical science data from the two redundant Probe Support Avionics (PSA), and critical engineering data. Critical engineering data consists of Attitude and Articulation Control Subsystem (AACS) engineering data and Radio Frequency Subsystem (RFS) engineering data.

There were four complete copies of the Huygens Probe data stored in telemetry partitions at the end of the Probe Relay Link. These copies were stored in dedicated telemetry partitions in both SSRs. The three telemetry Partitions were each sized to hold the data collected during the Probe Mission plus margin.

A navigational concern regarding slow converging Orbit Determination drove the Probe Relay sequence to have a late targeting vector update capability. Since certification of a critical sequence was a long and arduous process, recertification would have precluded a late sequence update. For this reason, an indirect commanding design was adopted, wherein the probe relay sequence required CDS to issue a command located outside the sequence memory. These indirect commands are AACS Vector Commands, were located in CDS Global Sequence Memory area, and were referred to as Global Vectors. A process was developed to generate Global Vectors, involving seven teams. Since the process was non-standard, several check points were incorporated into the process to eliminate vector errors. Figure 1 shows the final Global Vector Update Process.

2.4 System Level Testing At JPL

Cassini supports several layers of testing. System mode testing in the Cassini Integration and Test Laboratory (ITL) is the highest hardware fidelity simulation that Cassini still supports on the ground (see figure 2). This facility enables simulation of CDS, AACS and the Power and Pyrotechnic Subsystem (PPS) with the aid of Support Equipment Hardware and Software. The ITL provides verification and validation of the CDS and AACS subsystems, support for Cassini anomaly resolution and debugging, support for sequence and real-time command testing for the spacecraft, to develop test procedures for spacecraft testing, development and maintenance of Support Equipment Software and Hardware, support for Flight Software (FSW), development of functional procedures to test new capabilities and stress the FSW, support for the Science Instrument Flight Software Development and sequence testing, verification and validation of the Ground

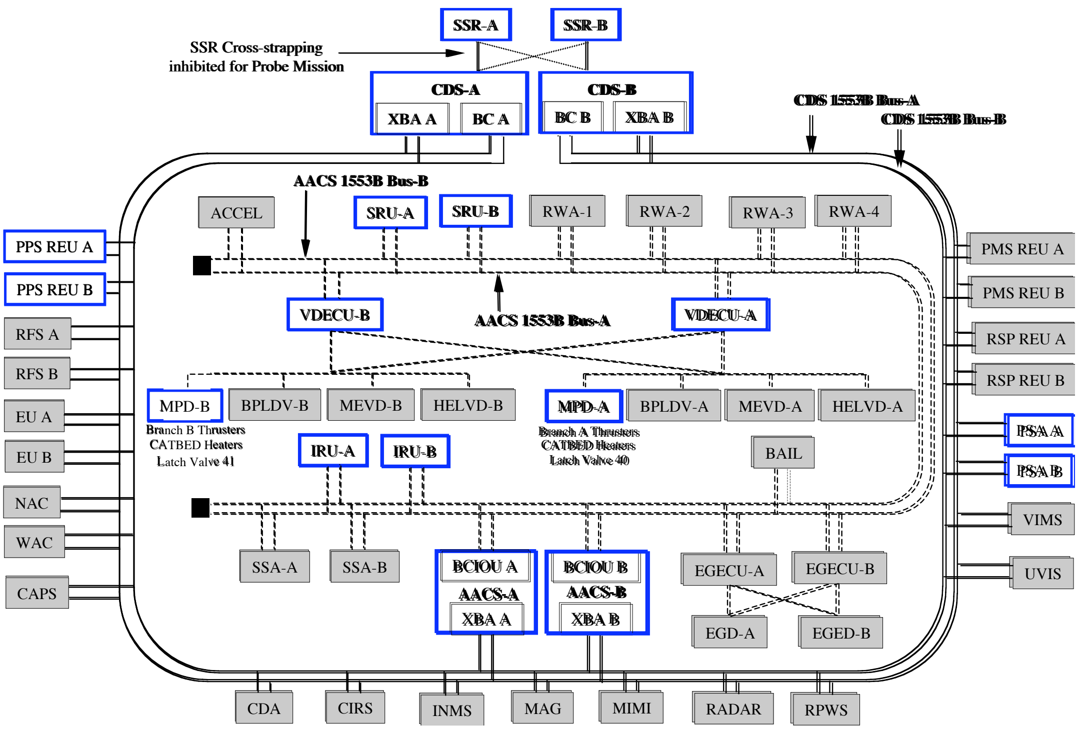

Figure 2. Integrated Test Laboratory Configuration for Cassini System Mode Testing. *The grey shading indicates hardware considered non-critical for the probe relay sequence*

System, critical sequence development (Saturn Orbit Insertion (SOI) and Probe Relay), testing and training, and Cassini spacecraft activity milestone dress rehearsals (FSW Uplink, SOI, Probe Relay).

A critical sequence must be certified through an extensive system mode testing program before it executes on the Orbiter. The ITL provides a system mode simulation with a real dual string CDS and dual string AACS configuration. The individual CDS and AACS subsystems consist of a mixture of flight hardware spares, Engineering Models and software simulations to accurately model the spacecraft performance. The ITL allows for realistic fault injection testing with proper interaction between AACS Fault Protection, CDS and System Fault Protection (SFP). Both Cassini and Huygens teams agreed to thoroughly review every test in a post test review. This review process required that each test be signed off by all personnel involved in the test.

3 LESSONS LEARNED

The Huygens mission has been a tremendous success, and the Cassini spacecraft is healthy and all subsystem performances are excellent. In the light of this success, there are some things that might be done differently if the operations were repeated. The following documents the lessons learned and our recommendations.

3.1 Atmospheric Model

In order to ensure that the Huygens descent profile was accurate, atmospheric measurements were made during Cassini Titan flybys before the probe mission began. This was done to determine the measured density, composition and wind profiles of the Titan atmosphere. After the first targeted flyby, T_a on 26 October 2004, the science data necessary to compute the measured atmospheric density during the flyby was collected and analyzed. At the same time, the Cassini AACS team studied the thruster telemetry during the flyby and derived the external torques from the Titan atmosphere as a function of time around closest approach. After receiving these deliveries, the Titan Atmospheric Model Working Group attempted to reconcile the AACS, INMS and other analyses to develop an integrated density and wind model. The process for validating the atmosphere model is documented in References 5 and 6.

A good atmospheric model was needed by several teams. Huygens operations needed an accurate model to support the descent analysis, and AACS needed the improved model to support lower altitude flybys at subsequent Titan encounters. The Titan Atmospheric Model Working Group (TAMWG) reconciled these various analyses and developed an integrated density and wind model for engineering use to ensure accuracy and sufficient conservatism.

Recommendation - It is extremely helpful to have a single entity, in our case the TAMWG, to coordinate the integration of an atmospheric model for the project.

3.2 Probe Imaging

Early in the mission planning phase, an activity to image the Probe after Probe Release was discussed. Probe imaging would contribute to the reconstruction of the Probe trajectory, it would provide inputs to the Huygens Descent Trajectory Working Group, it would provide confidence in a correct Probe separation and it would improve the knowledge of probe delivery parameters. On the other hand, since there was no real time operational criticality to the data, its collection could have been a distraction during a complex portion of the mission.

Eventually three post Probe Release imaging sequences were built, consisting of 5x5 OPNAV mosaics. The argument that swayed the decision is not in the above list. This argument was “What if we never hear from the Probe again, how can we verify that we released in the right direction?”

Recommendation - Mission activities should not be limited to only those activities that simply support the critical path, but should include those activities like the post Probe Release imaging that might be needed to support a post anomaly investigation.

3.3 Probe Checkouts

During the cruise phase, Huygens was activated for scheduled bi-annual checkouts. There were 16 Probe Checkouts before the Probe mission. These in-flight checkouts, which lasted between 3 and 4 hours, had been designed to follow as closely as possible the pre-programmed descent scenario. The purpose of the Probe checkouts was to perform periodic instrument maintenance and regular payload sensor calibration (Reference 7).

Data from the last Probe Checkout was assessed by HPOC and industry and were used as inputs to subsequent probe configuration decisions. These decisions were on whether to use the Transmitter Ulta-Stable Oscillator (TUSO) or Temperature Compensated Crystal Oscillator (TCXO) for the probe mission, whether to load the Mission Timer Unit (MTU) via

CDMU A or B, and whether to proceed with the primary mission opportunity at T_c. If there had been a serious malfunction of the Probe or the Support Avionics, release would have been delayed until the contingency opportunity at T_d or later. These decisions were to be made at the Go/No-Go for Primary Mission on December 2, 2004. (Reference 1). The checkouts were essential, since the activity provided health status of the Probe.

Recommendation – To provide adequate health and safety assessments, carry out periodic systems checks.

3.4 Risk Mitigation

A risk management process was established at JPL to address risk to the Cassini mission. The risk management effort at JPL was focused on the orbiter and the orbiter-to-probe interface. ESA also established a risk management effort to address risks specific to the Huygens Probe and its suite of instruments. A complete description of ESA-NASA collaborative risk management for the Huygens probe mission is given in Reference 4.

As a result of the mission recovery work, we saw significant changes to the planned activities, and those changes brought on new potential risks. Risk assessments were made periodically, and risks were prioritized and addressed accordingly.

Recommendation - Mitigate risks by methodical efforts through a process that assesses, prioritizes, and addresses each issue.

3.5 Resource Allocation

Missions like Huygens can easily be underestimated in their nature and complexity. Adequate resources should be allocated to the mission to allow for the necessary operational structure as understanding of the mission develops. Multitasking teams, such as those used at ESOC with SMART-1 and Huygens, are not always appropriate. Teams that split their attention between two demanding projects will divert resources to the project that is perceived as being in the biggest trouble at any given time.

Recommendation - Operational plans should address the backup of key personnel during critical periods when multi-tasking teams are used.

3.6 Probe Battery Depassivation

The probe batteries were charged before integration with the probe and Cassini; by design it was not possible to recharge them from the Cassini bus during the journey to Saturn. The purpose of battery depassivation was to remove a thin chemical passivating layer that forms within the lithium battery cells, on the surface of their electrodes, when no current flows. This layer, which builds up naturally over time, enables the cells to retain their charge during the long Cassini cruise phase but could be problematic for operations during the Probe mission.

Battery depassivation was performed twice. After the first battery depassivation, Huygens was able to validate excellent battery performance and that the Probe was ready for the Probe Mission.

Recommendation - Validate untested critical hardware prior to mission critical usage and allow schedule time for retesting.

3.7 U.S. Regulations

The United States must work within the structure of the International Traffic in Arms Regulations (ITAR) and the Export Administration Regulations (EAR). ITAR deals with the export of defense information under the U.S. Arms Export Control Act. ITAR restricts disclosure of technical data to a foreign national (foreign in this context meaning non-U.S.) whether in the U.S. or abroad. Technical data includes any information pertaining to the operation, testing, or modification of spacecraft or ground systems. Technical data under the Commerce Department's EAR (Export Administration Regulations) is specific information required for the development, production, or use of a product which itself is controlled. In order to not be considered "technical data" under ITAR, information must be either published and in the public domain, it must be made available by a federal agency, it must be "fundamental research", it is technical information which does not rise to the level of detailed technical information (public brochures, marketing pamphlets, general systems descriptions), or it is simply not technical information (like mission milestones, schedules, etc.) JPL implements ITAR very seriously to ensure the Cassini project technology is protected in accordance with ITAR.

Obtaining technical information from a project outside of the Cassini project was not easily done. For example, it would have been pertinent to pass Mars Exploration Rover (MER) parachute dynamics data to the Huygens team. The NASA-ESA Memorandum of Understanding (MOU) allows for exchange of data within the Cassini and Huygens projects, but does not allow for exchange of information from other projects within these regulations. Exporting technical information from another JPL project can only be done with the approval of NASA Headquarters. The whole process for obtaining approval was not well understood by JPL during the early co-location, with access to some routine documents causing delays; however the rapid build up of good working relations eventually resolved this problem.

Recommendation - Properly plan and implement the interface with international partners to minimize potential impediments and ensure compliance with the U.S. International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR).

3.8 Mission State Tracking

Cassini incorporates several tools and checklists to track states. In the case of the Huygens RUSO misconfiguration, these tools and checklists were not enough, as the RUSO was not tracked as a system-level state. There were no requirements within the Cassini documentation that stated there was a need to send Huygens subsystem commands during the Probe Relay critical sequence. The details from the Huygens operational requirements needed to be included in the requirements of Cassini. This could have been incorporated in either the Probe Interface Requirements Document (IRD), Orbiter Functional Requirements, or lower level requirements document.

Recommendation - Make every effort to include detailed operational requirements needed to implement the mission into the interface requirements.

3.9 Test Simulations

Both Cassini and Huygens ran simulations with as much high fidelity hardware as possible. The idea of operating the Cassini spacecraft simulator with Huygens Engineering Model (EM) was addressed on many occasions, but we were unable to implement this test configuration. As a work around, Cassini developed a simple PSA software simulator. This PSA simulator was only used to generate realistic data flow - PSA superpackets and housekeeping packets. The data inside both the PSA superpackets and housekeeping packets consisted of a ramping pattern. This PSA simulator provided no real PSA subsystem status.

Implementation of BITE Mode was recommended by the HRTF. Proper implementation of BITE Mode on Cassini required sending thousands of repetitive Huygens commands. A spare Automatic Temperature Control (ATC) algorithm was modified to issue 2 BITE Mode commands to the PSAs every 12 seconds. The commands were implemented by Cassini CDS and verified by Huygens. Again, members of the HIT were able to support the Huygens Mission redesign. When BITE Mode was identified by the HRTF, implementation and verification of two commands were simple. A simple review of the bus traffic by Huygens easily determined that the two Huygens commands were built correctly. It appeared that the PSA simulators were adequate for testing. Real PSAs or high fidelity PSA simulators would have been beneficial, because with more realistic PSA telemetry the failure of the RUSO to turn on would have been obvious.

Cassini had two critical sequences in concurrent development. The Saturn Orbit Insertion (SOI) sequence development took more intense reviewing than planned. This resulted in a temporary suspension of Probe Mission sequence testing until after SOI. When testing was resumed, the shortened schedule allowed only one complete Probe Mission end to end simulation, and the Flight Procedure redlines were accepted without retesting. This resulted in accepting a sequence that didn't reposition one of the SSR pointers. This error, which was minor, was caught after a request by management for a mental walk-through of all expected states at the beginning of the quiet period prior to the Probe Relay. This alternate SSR pointer position was retested in the ITL to the as flown Orbiter state and was determined to be acceptable as is. This minor mistake was caught 7 days prior to Probe Relay.

Recommendation - End to end mission simulations often identify problems, therefore these simulations should be run until a simulation without redlines to procedures can be completed. Simulations should also strive for high hardware fidelity between interfaces with international partners.

3.10 Interface Agreements

Early in the mission, there was a formal interface between ESA and NASA, with a relatively high level Interface Requirements Document from which requirements flowed down to Interface Agreements. These defined the necessary exchange of data products, System Interface Specifications (SIS) that defined the necessary hardware and software connectivity, and documented interface specifications for all aspects of the Cassini-Huygens interface. These measures are necessary on every joint project of this complexity and scope.

Formal interface agreements for the data products that could be well defined and structured worked very well, but there were many necessary interactions with our international partners that could not be easily defined as a file exchange. Interface agreements are an invaluable tool when an aspect of a complex interface can be reduced to a mere file exchange, but many aspects of an interface between two space agencies cannot be well served by such devices and must have the support of face to face contact.

The navigation interface was a very good example of this; of all the aspects of the Cassini-Huygens partnership this was the one most conducive to clearly structured interface agreements, but even in this case the interface benefited enormously from having a Huygens team member co-located with Cassini Navigation.

Recommendation - Normally interface agreements are an invaluable tool when dealing with complex interfaces, but in addition to interface agreements co-location of teams allows for a more adaptive approach.

3.11 Process Development

Huygens Mission Operations Plan (MOP) describes the road map for the Huygens Probe Mission. In this plan, decision points were identified and possible alternate paths were documented. On reexamining the MOP, it was found that Cassini and Huygens personnel had understood a particular branch differently. Huygens had been proceeding on a mission design that expected sequence updates to the Probe Relay Critical Sequence such as vector updates and RUSO On or Off. The later change corresponds to the Final Probe Checkout decision to use either the TUSO or TCXO on the Probe. Although this decision point was always clear, it was not clear that a decision to use the TUSO on the probe would result in a change to the Critical Sequence to also turn on the RUSO. Cassini proceeded on a mission design that expected only vector updates to the Probe Relay Critical Sequence.

Recommendation - Take the time to explore each decision path in a process flow diagram with the whole team and ensure that paths requiring an action are reported back into the process at future decision points and that the implications of those actions are well understood.

3.12 Special In-Flight Tests

Two special in-flight tests were flown that should be noted. In the first test, the Probe Support Avionics (PSA) were activated without the Probe to support an in-flight end-to-end test of the receiving elements of the Huygens telecommunication system. This end-to-end test was carried out by using a NASA Deep Space Network Antenna to mimic the Probe radio transmissions. A Huygens receiver anomaly was discovered as a result of the first end-to-end test in February 2000.

In March 2004, a Probe Relay In-flight Demonstration was executed on the spacecraft. The In-flight Demonstration executed a nearly identical sequence to the sequence that was used on 14 January 2005. The PSAs were powered on and the RUSO was not powered on during this demonstration. The Cassini-Huygens spacecraft performed nominally. A full data set was collected and played back for Huygens. This data set was successfully transmitted to HPOC validating the recent upgrade to the ground data transfer process.

Recommendation - Special in-flight tests flown in realistic mission conditions provide valuable system validation and if performed early enough provide time for mission recovery.

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ACKNOWLEDGEMENT

This work described in this publication was performed at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract with the National Aeronautics and Space Administration. The Cassini/Huygens mission is a joint undertaking by the National Aeronautics and Space Administration, the European Space Agency, and the Agenzia Spaciale Italiana. This work was carried out for the Cassini-Huygens Program at the Jet Propulsion Laboratory, California Institute of Technology, under contract from National Aeronautics and Space Administration. The Authors would like to thank Dr. Claudio Sollazzo, the ESA Huygens Mission Operations Manager, Robert Mitchell, the Cassini Program Manager, Dr. Earl Maize, the Cassini Deputy Program Manager, and Julie Webster, the Cassini Spacecraft Operations Manager, for their help and encouragement in writing this paper.